NATIONAL ADVISORY COMMITTEE
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TECHNICAL NOTE 2758

WEAR AND SLIDING FRICTION PROPERTIES OF NICKEL ALLOYS

SUITED FOR CAGES OF HIGH-TEMPERATURE

ROLLING-CONTACT BEARINGS

I - ALLOYS RETAINING MECHANICAL PROPERTIES TO 600° F

By Robert L. Johnson, Max A. Swikert
and Edmond E. Bisson

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

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SUMMARY

Wear and sliding friction properties of a number of nickel alloys
operating against hardened SAE 52100 steel were studied. These alloys
include "L" nickel, wrought monel, cast monel, cast modified "H" monel,
cast "S" monel, Invar, Ni-Resist 3, and Nichrome V. Some of the alloys
studied may be useful as possible cage materials for high-temperature,
high-speed bearings for aircraft turbines or for bearings to operate in
corrosive media.

Desirable operating properties of all the materials could be
associated with the development on the rider surface of a naturally
formed film of nickel oxide. On the basis of wear and friction proper-
ties, Ni-Resist 3, modified "H" monel, and Invar were the best materials
studied in this investigation although they did not perform as well as
nodular iron. The "L" nickel performed well with light loads but was not
effective at higher loads when the surface film broke down.

INTRODUCTION

Cages (separators or retainers) have been a principal source of
failure in the rolling-contact bearings of aircraft turbine engines
(references 1 and 2). These failures are generally lubrication failures
and occur at the cage locating surfaces as indicated in figure 1. Refer-
ence 3 discusses the conditions leading to failures at the cage locating
surfaces (high soak back temperatures, low length-diameter ratio, mis-
alinement, thermal distortion, etc.). The combined effect of these
conditions is the occurrence of extreme boundary lubrication and metallic
adhesion which lead to the ultimate deterioration of mating surfaces.
The current design trend in aircraft turbine engines is toward higher
operating temperatures, higher surface speeds, and less viscous
lubricants. These factors will serve to increase the severity of the
cage problem for rolling-contact bearings.

One means of reducing the severity of this problem is to make the cages of improved bearing materials, that is, of materials which have inherent "antiweld" characteristics under marginal conditions of lubrication. As noted in reference 2 some measure of protection from welding was obtained by silver plating one of the currently used cage materials (bronze).

The currently used cage materials (brasses and bronzes), which operate at temperatures less than 600° F, will probably be found inadequate from the standpoint of both strength and welding for cages of bearings operating at temperatures from 400° to 600° F; it is possible the nodular iron suggested as a cage material in reference 3 may also be found inadequate from a standpoint of strength at these temperatures. Among others, the requirements for a cage material to operate at high temperatures are as follows: (1) adequate strength, (2) corrosion resistance, and (3) antiweld properties. (It is considered that a desirable cage material might have mechanical properties at proposed operating temperatures that are approximately equivalent to the mechanical properties of the materials in current use at present operating temperatures). A number of materials that might have adequate strength and corrosion resistance at the proposed operating temperature are alloys containing relatively large amounts of nickel. Nickel alloys have not generally been considered as good bearing materials up to the present time; however, very little information on friction and wear properties is available. The only nickel alloy known to have been used as a cage material is monel and its performance has been erratic (reference 3). Beside their use at high temperatures under normal operating conditions, nickel alloys might also be useful for cages of bearings intended for operation in corrosive media, such as combustion gases, rocket propellants, and liquid metals. These conditions may be encountered in turbine engine auxiliaries and in new-type power plants for aircraft.

The research reported herein was conducted at the NACA Lewis laboratory to study the friction and wear properties of several nickel alloys that could be considered for use in cages of rolling-contact bearings at temperatures below 600° F. (Studies of materials to operate in the temperature range above 600° F are reported in reference 4). The sliding friction experiments described herein were not simulated cage tests but were made to obtain fundamental, comparative information on friction and wear properties which are a general measure of adhesion.

Because high-temperature equipment was lacking these runs were made at room temperature. It is generally true, however, that materials having good friction properties at room temperatures will also have good friction properties at elevated temperatures provided they have sufficient mechanical strength. During sliding, temperatures of contacting asperities approach the melting point of one of the materials regardless of ambient temperatures.

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The friction and wear experiments were conducted with loaded hemispherically shaped specimens of different nickel alloys sliding in a continuous path on rotating steel disk specimens at room temperature. Most experiments were run at a sliding velocity of 5000 feet per minute with loads from 50 to 1593 grams. Wear debris was studied by means of X-ray diffraction techniques. The nickel alloys studied are as follows, listed in order of decreasing nickel content: cast monel, cast modified H-monel, cast S-monel, Invar, and Ni-Resist 3. "L" nickel was included for comparison purposes (as was wrought monel and Nichrome V from reference 3). The data were obtained under both dry and boundary-lubrication conditions.

MATERIALS

The materials used in this investigation have acceptable mechanical properties at temperatures to 600° F. The strength of these materials at 600° F generally compares favorably with the strength of the currently used bronze materials at ordinary temperatures.

The materials studied, their compositions, and some of their typical properties are listed in table I. Although most of the values given in table I are published data, the hardnesses were found comparable with data obtained by means of a Rockwell superficial hardness tester. Initial surface-roughness values for the disks were obtained with a profilometer. The properties of "L" nickel, wrought monel, and modified "H" monel, cast "S" monel, and Invar were obtained from reference 5 and other International Nickel Company Inc. publications. The composition of the cast modified "H" monel was obtained from the Marlin-Rockwell Corp. The data on centrifugally cast monel were supplied by the Janney Cylinder Co. Information on Ni-Resist, type 3, was obtained from the Electroalloys Division of the American Brakeshoe Company.

The photomicrographs (X100) of metallographic specimens of the alloys used in the friction and wear experiments reported herein are shown in figure 2. These photomicrographs show the types of structure and the relative grain size of the various alloys investigated.

Because the proper materials were not available, all the nickel alloys were run against SAE 52100 steel (Rockwell hardness C-60 - C-62) as one of the specimen materials even though this steel will be unsatisfactory for operation under high-temperature conditions. The materials of most promise at the present time for the races and rolling elements of bearings to operate at high temperatures appear to be the molybdenum tool steels; these steels, in sizes required for the disk specimens of these experiments were, however, unavailable at the time of this investigation. Indications are that the results with the tool steel disks may not be too much different (at equal hardnesses) from those with SAE 52100 steel disks.

APPARATUS AND PROCEDURE

Specimen preparation. - In each experiment there were two specimens, the rider and the disk. The rider specimens of the materials being investigated were cylindrical (3/8-in. diam., 3/4-in. length) and had a hemispherical tip (3/16-in. rad.) on one end. The surface of the rider specimens was finished by fine turning using minimum material removal per cut in order to minimize surface cold working. The disk specimens (13-in. diam.) were circumferentially ground on a conventional surface grinder with light grinding pressures to produce a surface roughness of 10 to 15 rms as measured with a profilometer. These values of roughness are within the range of roughness measurements obtained on cage locating surfaces of representative rolling-contact bearings (reference 6).

The rider specimens were cleaned before each experiment with a clean cloth saturated with redistilled 95-percent ethyl alcohol. The disk specimens were carefully cleaned to remove all grease and other surface contamination according to the detailed procedure given in reference 7. Briefly, this cleaning procedure includes scrubbing with several organic solvents, scouring with levigated alumina, rinsing with water, washing with ethyl alcohol, and drying in an uncontaminated atmosphere of dried air.

Friction apparatus. - The friction apparatus used for these experiments is essentially the same as that described in reference 7. A diagrammatic sketch of the apparatus showing the holder assembly for the rider specimens and the rotating disk specimen that are the primary parts is presented in figure 3. The disk is rotated by a hydraulic motor assembly that provides accurate speed control over a range of sliding velocities from 75 to 18,000 feet per minute. The disk specimen was mounted on a flywheel assembled with its shaft supported and located by a mounting block which contained bearing assemblies for accurate location. Loading was accomplished by placing weights along the axis of the rider holder. Friction force was measured by four strain gages mounted on a beryllium-copper dynamometer ring and connected to an observation-type potentiometer converted for use as a friction-force indicator. The strain gages were so mounted that temperature compensation was obtained. The coefficient of friction μ_k is calculated from the equation

$$\mu_k = \frac{F}{P}$$

where F is the measured friction force and P the applied normal load. The reproducibility of the coefficient of friction values in all but isolated cases was within ±0.04 for dry surfaces and within ±0.02 for lubricated surfaces. The data presented are complete data from a representative experiment on each variable.

Friction-force readings are recorded by a motion picture camera (64 frames/sec) timed to operate for 3 seconds covering each separate friction run.

Method of conducting experiments. - Wear runs of 3 hours duration were made on dry surfaces with loads of 50 and 269 grams at a sliding velocity of 5000 feet per minute. All runs were made at room temperature. The complete run was made over the same wear track (without radial traverse of the rider specimen). Wear of the rider was determined at regular intervals from measurements of wear-spot diameter made with a calibrated microscope and by weight loss obtained with an analytical balance. The final wear-volume measurements could generally be reproduced within ±10 percent in different experiments on a given material. Weight-loss measurements were used as a rough check on the accuracy of the wear-spot-diameter data. No wear measurements were made of the slider (disk) specimen.

Friction runs to determine effect of loading were made with boundary-lubricated surfaces at a sliding velocity of 5000 feet per minute with increasing loads in increments from 119 grams to the failure point of the specimens. The disk was lubricated before each 3 second run by rubbing a very thin film of petroleum lubricant grade 1005 (Air Force specification 3519, Amendment 2) on the rotating surface using lens tissue. Previous experience at this laboratory has indicated that the film formed by this procedure is sufficiently thin that hydrodynamic lubrication will not occur. Reference 8 shows that a lubricant film of this type may approach a monomolecular film at the points of the surface asperities. Surface failure was established by both increased friction values and the occurrence of welding (visible metal transfer).

The loads and the specimen shapes were so chosen as to produce relatively high initial surface-contact stresses. In spite of the relatively light loads and large apparent areas of contact of the cages at their locating surface in rolling-contact bearings under normal conditions, the actual contact stresses can be large. As discussed in more detail in reference 9 (pp. 10-32), surfaces under nominal load and with large apparent areas of contact can have stresses at the localized contact areas that are equal to the flow pressure (compressive yield strength) of the materials at the contacting asperities.

RESULTS AND DISCUSSION

As previously stated, the antiweld properties of cage materials are of primary importance, in fact, in many cases the antiweld or surface failure properties are of greater importance than the friction properties. The first stage of surface failure is a breakdown of whatever adsorbed film of fluid lubricants may be present and the second stage is the contact of metals free of fluid lubricant. This condition increases the severity of temperature flashes which increases the susceptibility to

surface adhesion. Subsequently, incipient surface failure occurs; this
condition is usually detected by increased friction and it is manifested
by minute surface welds or rapid abrasion. The ultimate point of failure
is complete seizure or mass welding of the surfaces. In many cases, mass
welding does not produce the violent frictional behavior that might be
anticipated. Surface temperatures that accompany mass welding are gener-
ally extremely high (approaching the melting point) and may result in the
welded junctions having such low shear strength that there is little or
no increase and possibly a decrease in friction. The presence of a
naturally formed reaction film such as an oxide may generally arrest the
progression of failure.

Because of the importance of surface failure, particular effort was
made in the studies described herein to detect its occurrence. Study of
the rates of wear and the appearance of the surfaces generally made it
possible to establish the initial occurrence of mass surface failure.

Wear of unlubricated surfaces. - The data of figures 4 and 5 show the
total wear volume at different time increments up to 3 hours (180 min.) for
each material at a sliding velocity of 5000 feet per minute with loads
of 50 (fig. 4) and 269 (fig. 5) grams. For both loads, "L" nickel had
the lowest wear rates; it should be recalled, however, that annealed
"L" nickel is included only for comparison purposes since it probably
does not have adequate strength.

While cast monel has relatively good wear properties at the light
loads, the heavier load changed the wear rate appreciably. Of the
materials included in this investigation therefore, those which show the
most promise from a wear standpoint under dry conditions are Ni-Resist 3,
modified "H" monel, and Invar.

Table II shows wear for all the materials studied as ratios of the
total wear (after 180 min.) relative to that for "L" nickel; these ratios
are based on data taken from figures 4 and 5. Table II also summarizes
film-formation and surface-failure properties of the materials of this
investigation; these properties will be described in detail as the
individual materials are discussed.

These wear data show an appreciable effect of load on the relative
wear rates of the different materials. Relatively large increase in
wear for "L"-nickel with the heavier load is probably a result of low
mechanical strength. In general, the use of relations based on the
physical properties of the material will not explain the wear properties
observed in obtaining the wear data as reported. The nonlinearity of
the wear curves presented in figures 4 and 5 indicate that wear is not a
function only of the mechanical properties of the materials and the
physical conditions of sliding. Rather, these data, as well as data
presented previously in reference 3, show the importance of the formation

of surface films on the metals. In many cases, abrupt changes in rate of wear (slope of the wear curves) can be related to the breakdown or formation of surface films on the rider specimens (e.g. Invar). It is by virtue of the surface film formed during sliding that "L" nickel, a material normally considered unacceptable for sliding surfaces, performs in a manner superior to several widely used slider materials.

For the materials of this investigation, conditions of the wearing surfaces were changeable; films were continually forming, wearing away, and reforming. Similarly, the coefficients of friction for most of the materials were quite changeable. In general, the initial friction coefficient values for all materials during the dry wear runs (0.25 to 0.35) were substantially higher than the subsequent values (0.10 to 0.15). The trend of reduced friction with continued running coincides with the formation of surface films and possibly cold working of the sliders. Exceptions to this trend include wrought monel for which friction increased with continued running time as the two conditions of a prohibitively high wear rate and surface failure were obtained.

Figures 6 and 7 present photographs of wear areas of several rider specimens after the runs of figures 4 and 5, respectively. Microscopic study of the surfaces of these specimens reveals conditions helping to explain the behavior of the material during sliding. The photograph of figure 6(a) shows the surface conditions of the "L" nickel specimen. This specimen had perhaps the best appearing running surface obtained in these experiments; it had a uniform black film on the wearing area and there was no sign of surface failure. The trailing edge of this wear surface shows evidence of plastically displaced metal resulting undoubtedly from the low yield strength of this material. The metals of higher yield strength did not, however, have as good film-forming properties as "L" nickel. When not subject to mass surface failure, all the monel specimens formed surface films in streaks as shown for cast monel in figure 6(b). The dark streaks are surface films or areas that appear to have been supporting the load. It was possible to focus a metallurgical microscope separately on the center of the light and dark areas shown in figure 6(b) and to show that the dark areas were higher than the light areas, thereby indicating that the dark areas were the bearing surfaces.

The films formed on the wear areas of the "L" nickel specimens run with a load of 269 grams (fig. 7(a)) were not as continuous as those formed with a load of 50 grams. Mass welding was, however, effectively prevented. Previous work (reference 10) under static friction conditions, where there was no opportunity for this type of surface film to form, has demonstrated that hardened steel and "L" nickel (as well as monel) weld readily when in the clean state.

Modified "H" monel (fig. 7(b)) when run with a load of 269 grams, produced the same sort of wearing surface that was generally observed for all cast monel metals with both the 50-gram (fig. 6(b)) and the

269-gram load. For these materials it is possible that the film formed, after which subsequent plastic deformation of the base metal could take place resulting in a mixture of the film and the base metal. This mixture of these two materials could produce a surface layer having less tendency to weld than the original metal.

The wear tracks on the disk specimens shown in figure 8 are the surfaces against which the slider specimen wear areas in figure 7 were run. In general, the wear tracks on the disk specimens showed either a uniform smearing of transferred metal or "globs" of welded metal from the rider specimens. The smeared surfaces were mostly coated with the same naturally formed films found on the rider specimens. The wear track on the disk specimen that operated against "L" nickel (fig. 8(a)) indicated the material had been transferred from the "L" nickel specimen to the disk; this transferred material then formed a dark film.

Modified "H" monel was more susceptible to surface welding than "L" nickel; many small globs of welded material were found on the wear tracks of the disk (fig. 8(b)). None of the rider materials caused significant damage to the disk surfaces; the running surfaces on the disks were, in fact, formed by transferred rider materials. It was probably only because of the films formed on the surfaces that mass welding was not common to all materials.

Where surface photographs are not included in this report the surface appearance of many of the specimens may be considered as being approximately represented by the figures that are included according to the comparison given in table III.

Friction of lubricated surfaces. - Under effective boundary-lubrication conditions, the material properties of the slider are of less importance than when marginal boundary lubrication occurs. Consequently, a series of runs was made with all the materials sliding on marginally boundary-lubricated disk surfaces; these results are presented in figure 9. The runs were made at a sliding velocity (5000 ft/min) that was intended to be above the break point of partial film failure for grade 1005 oil. As described in reference 11, the break point was approximately 2500 feet per minute. The data on the various slider materials were obtained with extremely poor boundary lubrication since it is under such conditions that the sliding properties of the materials are important. As compared with these data, when effective boundary-lubrication conditions are obtained, the friction coefficient values are generally in a range from 0.08 to 0.15 with petroleum lubricants.

Figure 9(a) presents friction data for the monels, and figure 9(b) presents data for the remaining nickel alloys. The cast monels used to obtain the data of figure 9(a) did not, generally, have as erratic friction values as wrought monel reported in reference 3. At loads under 500 grams, modified "H" monel showed little evidence of lubrication or surface failure.

At loads between 600 and 1000 grams, except for wrought monel, there was little difference in friction coefficient. At loads above 1000 grams, the cast monel had such erratic friction that it was impossible to obtain dependable values.

The friction coefficients for "L" nickel and Invar (fig. 9(b)) are much higher than those for the other alloys. At the higher loads the "L" nickel, and to a lesser extent the Invar, showed mass plastic flow adjacent to the surface. This condition produced erratic friction since the plastic nature of the metal made it impossible for a stable surface film to be formed.

The presence of a lubricant on the disk did not prevent the formation of surface films on the wear areas of the rider specimen. Wear areas of "L" nickel and modified "H" monel rider specimens after similar series of friction experiments are shown in figure 10. Annealed "L" nickel (fig. 10(a)) did not have sufficient yield strength to support the stress (corresponding to the maximum load of 1593 g) developed in these experiments. The irregularity of the wear spot as well as the surface appearance indicated that mass plastic flow of the material occurred when the rider specimen was overloaded; the presence of a film (which was apparent on the surface), however, prevented harmful surface welding. Modified "H" monel had a wear spot (fig. 10(b)) that again was characteristic of all the cast-monel materials. The film formation was nonuniform. There was evidence of surface welding on the modified "H" monel specimens.

X-ray diffraction study of wear debris. - Specimens of the black powder formed during the wear runs with the nickel alloys were obtained from the disk surface. X-ray powder patterns were taken with a Debye-Scherrer camera using manganese radiation. The d values for the wear debris from each alloy and the d values for standard materials are compared in figure 11. In figure 11(a) the d values of the alloys approach the d values of the face-centered cubic nickel. The slight variations were caused by the influence of the alloying elements in the space lattice of the nickel. Therefore, "L" nickel was used as a standard to compare with the d values of the debris. As is evident in figure 11(b) nearly all the diffraction patterns of the wear debris from various materials contained lines corresponding to the standard pattern of "L" nickel. At d values of 2.06, 1.46, and 2.4 Angstrom units, however, other lines are apparent in many of the patterns. These lines correspond generally to the A.S.T.M. d values for nickel oxide. Figure 11(b) is therefore set up with two known patterns, the "L" nickel standard and the nickel oxide bracketing the patterns obtained from debris of the various materials. Thus, it is seen that the diffraction data indicate that both the nickel oxide and the original alloy are present in the wear debris. The lines of nickel oxide corresponding to d values of 2.07 and 1.27 Angstrom units in most cases cannot be resolved from the lines of the standard alloy. Extra lines are observed in the wear debris pattern of "L" nickel; these lines may be due to different forms of the oxide.

The exact proportion of oxide to alloy could not be determined from these diffraction data but it was apparent that some of the wear debris samples contained more oxide than others. The most noticeable was the wear debris from "L" nickel. The diffraction pattern shows that it consists almost entirely of oxide (fig. 11(b)). On the other hand, diffraction patterns from the wear debris of the monels showed that only small amounts of oxide (if any) were present. For example, it is questionable on the basis of diffraction data, whether much oxide is present in the debris from modified "H" monel and from "S" monel. As a very general rule, it was found from observations of the diffraction intensities that those materials which resulted in the least wear yielded wear debris containing the greatest percentage of oxide to alloy. This condition is consistent with the consideration that the naturally formed oxide film is an effective solid lubricant which reduces wear and surface damage.

Practical significance. - Consideration of all the data presented, as well as all the other factors of practical importance, indicate that, of the materials included in this investigation, Ni-Resist 3, modified "H" monel, and Invar are probably the most suited for sliding surfaces under conditions of extreme boundary lubrication. These three materials may, however, not be as well suited as the nodular iron of reference 3. The diffraction data indicate that Ni-Resist 3 readily forms a film which diffraction data indicate is a nickel oxide. The coefficient of thermal expansion of Ni-Resist 3 (5.25×10^{-6}) makes it appear that this material would be more suited to rolling-contact bearings with outer-race riding cages than with inner-race riding cages because of thermal expansion effects at the elevated temperature. Modified "H" monel with a coefficient of thermal expansion of 6.8×10^{-6} appears best suited for inner-race riding cages. Invar, with a coefficient of thermal expansion of 0.6×10^{-6}, may be suited for particular applications requiring little dimensional change with temperature.

The experiments indicate that the friction and surface failure properties of the nickel alloys are dependent to a large extent on the formation of oxide films on the running surfaces. In consequence, the atmosphere, which most likely supplies the necessary oxygen for film formation, is very important to the proper functioning of the material as sliding surfaces. Caution must therefore be used in employing these materials for sliding surfaces designed to operate in inert or reducing atmospheres.

Under static-friction conditions the beneficial oxide films would not usually form but under sliding-friction conditions the probability of film formation is enhanced by high surface temperatures. Most data available on friction behavior of nickel and nickel alloys are static-friction data. Those data indicate undesirable frictional properties, which have led to the general opinion that nickel alloys are not suitable

for sliding surfaces. It therefore appears that a lack of understanding of the behavior of nickel and nickel alloys under sliding conditions may have prevented their use in the solution of many problems. In practical applications the formation of oxide films on the contacting surfaces during initial operation would probably protect these parts in subsequent failure during static or shutdown periods. Pretreatment of the contacting surfaces to form oxides might be necessary to insure against surface damage in the initial period of operation, until the natural oxide films are formed.

The data of these experiments do not make it possible to arrive at any conclusion regarding the effect of metallurgical structure on wear and friction properties. With materials having similar compositions, however, it was found that the cast metals perform in a manner superior to the wrought form of the metal. The best example of this result is a comparison of wrought and cast monel (figs. 4 and 5).

Preliminary experiments at room temperature with the materials of this investigation against disk specimens of 18-4-1 tool steel showed the same general trend obtained with disk specimens of SAE 52100 steel.

The data reported herein were obtained at room temperature; however, the general trends observed (particularly the surface welding and friction properties) are believed to indicate what might be expected at the temperatures of interest. Reference 9 indicates that friction is affected only slightly by temperatures even as high as 1000° C. The mechanical strength and chemical (for example, oxidation) behavior of the materials of this investigation (both disk and rider specimens) are not significantly affected by the temperatures considered.

SUMMARY OF RESULTS

Investigation of wear, friction and surface failure properties of dry surfaces and of boundary-lubricated surface of "L" nickel, monel, wrought monel, cast monel, modified "H" monel, "S" monel, Invar, Ni-Resist 3, and Nichrome V sliding on hardened SAE 52100 steel were conducted at room temperature. The alloys investigated may be useful as possible cage materials for high-temperature rolling-contact bearings of high-speed turbine engines. The research produced the following results:

1. Desirable operating properties of all the materials studied could be associated with the development on the rider surface of a naturally formed film which X-ray diffraction patterns indicated was predominately nickel oxide. High-temperature operation in air would accelerate formation of the beneficial surface film; in consequence, the best of these materials could perform well in cages of high-temperature rolling-contact bearings. Pretreatment to form a surface film before operation would probably be beneficial.

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2. On the basis of wear and friction properties Ni-Resist 3, modified "H" monel, and Invar were the best of the materials studied in this investigation although they did not perform as well as nodular iron. Of these materials, Ni-Resist 3 showed the best film-formation properties. The first two materials have thermal expansion coefficients approaching that for steel, Ni-Resist 3 being less than and modified "H" monel being greater than that for SAE 52100. Cast modified "H" monel showed the inconsistent performance characteristic of monel metals which results from erratic surface film formation. In general, cast monels have better friction and wear properties than the wrought form of these metals.

3. Annealed "L" nickel performed very well at light loads but had insufficient yield strength for operation with the heavy loads.

Lewis Flight Propulsion Laboratory
    National Advisory Committee for Aeronautics
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TABLE I - TYPICAL VALUES FOR PROPERTIES OF MATERIALS

Material	Nominal composition (percent)	Tensile strength (lb/sq in.)	Yield strength (lb/sq in.)	Brinell hardness	Modulus of elasticity	Density (lb/cu in.)	Coefficient[a] of thermal expansion (in./in./°F)	Coefficient of thermal conductivity (Btu/(sq ft)(hr)(°F/in.))	Melting point (°F) (approximate)
"L" nickel (annealed)	99.4 Ni 0.02 C (max) .1 Cu .15 Fe .2 Mn .05 Si	$60{\times}10^3$	$15{\times}10^3$	90	$30{\times}10^6$	0.321	$7.2{\times}10^{-6}$ (32°-212° F)	420	2625
Monel (wrought)	67.0 Ni 30.0 Cu 1.4 Fe 1.0 Mn	$110{\times}10^3$	$100{\times}10^3$	[b]240	$26{\times}10^6$	0.319	$7.8{\times}10^{-6}$ (32°-212° F)	180 (32°-212° F)	2460
Monel (cast centrifugally)	67.0 Ni 29.0 Cu 3.0 Fe 1.50 Mn	$65{\times}10^3$	$32.5{\times}10^3$	110	[c]$19{\times}10^6$	[c]0.312	$6.8{\times}10^{-6}$ (32°-212° F)	180 (32°-212° F)	[c]2425
Modified "H" monel (cast)	62.06-62.8 Ni 31.43-32.3 Cu 1.49- 1.95 Fe 3.25- 3.66 Si 0.53- 0.76 Mn .016- .025 C	[c]$100{\times}10^3$	[c]$60{\times}10^3$	[c]210	[c]$20{\times}10^6$	[c]0.305	$6.8{\times}10^{-6}$ (32°-212° F)	[c]180	[c]2375
"S" monel (cast)	63 Ni 30 Cu 4 Si 2 Fe	$130{\times}10^3$	$100{\times}10^3$	320	$21{\times}10^6$	0.302	$6.8{\times}10^{-6}$ (32°-212° F)	180	2325
Invar (hot-rolled)	36 Ni 64 Fe	$75{\times}10^3$	$50{\times}10^3$	140	$21{\times}10^6$	0.292	$0.6{\times}10^{-6}$ (32°-212° F)	73	2600
Ni-Resist (type 3)	28.91 Ni 1.76 Si 62.5 Fe 3.47 Cr 2.58 C	$25\text{-}35{\times}10^3$	$13.5{\times}10^3$	120- 150	15 to $15.5{\times}10^6$	0.267	$5.25{\times}10^{-6}$ (70°-400° F)	232	2250
Nichrome V (wrought)	80 Ni 20 Cr	$110{\times}10^3$	$63{\times}10^3$	90	$31{\times}10^6$	0.303	$9.8{\times}10^{-6}$ (70°-1800° F)	166 (104°-212° F)	2550

[a]For comparison with: SAE 52100 steel, $6.49{\times}10^{-6}$ (77°-300° F); 18-4-1 tool steel, $6.6{\times}10^{-6}$ (80°-400° F).

[b]Measured.

[c]Estimated, based on similar materials.

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TABLE II - SUMMATION OF WEAR, FILM-FORMATION, AND SURFACE-FAILURE PROPERTIES OF SEVERAL NICKEL ALLOYS

	Load (g)	MATERIALS							
		"L" nickel	Nichrome V	Monel (wrought)	Monel (cast)	Modified "H" monel	"S" monel	Invar	Ni-Resist 3
Relative amount of total wear volume as ratio of total wear volume for "L" nickel	50	1.0	10.2	9.1	3.5	5.9	9.7	6.0	4.6
	269	1.0	4.5	(a)	7.2	2.2	3.9	2.3	1.4
Film-formation properties		Film formed readily: film spalled at high loads.	Nonuniform noncontinuous film formed.	Noncontinuous film at light loads; no film formed at high loads.	Noncontinuous films formed.	Noncontinuous film formed.	Noncontinuous film formed.	Film formed readily; spalled slightly at high loads.	Noncontinuous film formed.
Surface-failure properties		No welding; excessive plastic deformation at high loads.	No mass surface welding; incipient welding at loads greater than 800 g.	Inconsistent welding at light loads; plastic deformation at high loads.	Some welding and metal transfer to disk specimen.	Some welding and metal transfer to disk specimen.	Some welding and metal transfer to disk specimen.	Some metal transfer to disk specimen.	Some welding and metal transfer to disk specimen.

[a]Run terminated after 15 min.

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TABLE III - COMPARISON OF SURFACE CONDITIONS OF SPECIMENS

[For specimens which do not have surface photographs included in
the report, the figure number of a photograph approximately
representing the surface appearance is given instead.]

Experiment	Materials							
	"L" nickel	Nichrome V	Monel (wrought)	Monel (cast)	Modified "H" monel (cast)	"S" monel (cast)	Invar	Ni-Resist 3
	Figure							
Rider specimen, 50-gram wear run	6(a)	(1)	(2)	6(b)	6(b)	6(b)	---	(3)
Rider specimen, 269-gram wear run	7(a)	(1)	(2)	7(b)	7(b)	7(b)	7(a)	---
Disk wear track, 269-gram wear run	8(a)	(1)	(2)	8(b)	8(b)	8(b)	8(b)	8(b)
Rider specimen, lubricated	10(a)	(1)	(2)	10(b)	10(b)	10(b)	10(a)	10(b)
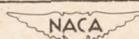
[1]Photograph in reference 3 which shows black oxide film.

[2]Photograph in reference 3 which shows severe plastic deformation.

[3]Somewhat similar to figure 7(b) except without evidences of cold-working.

Lubrication
failures

Cage

Lubrication
failures

Lubrication
failures
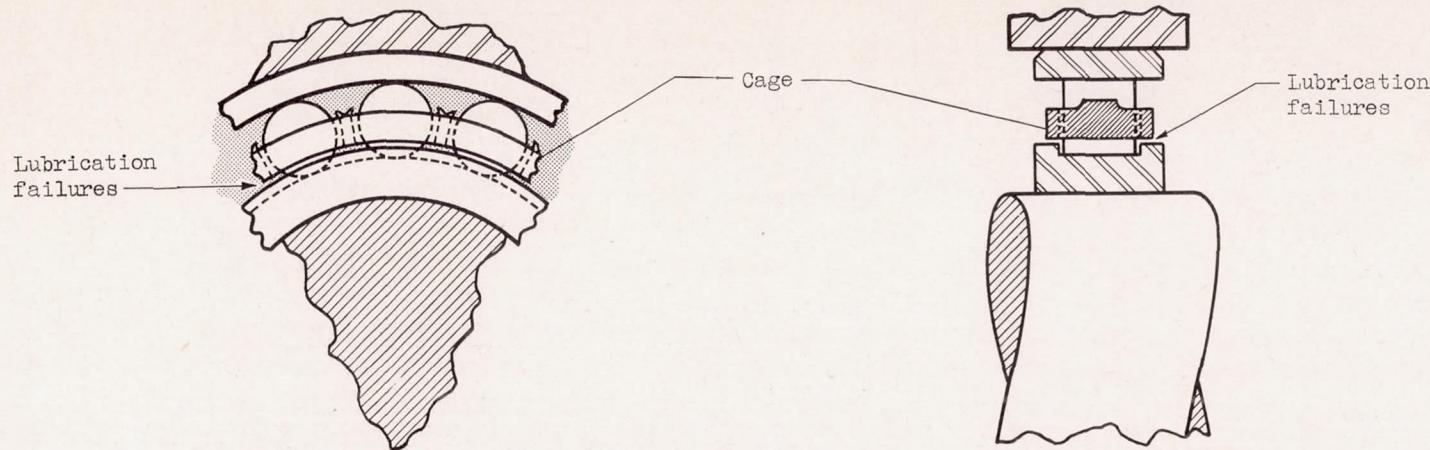
(a) Inner-race riding cage.

Lubrication
failures
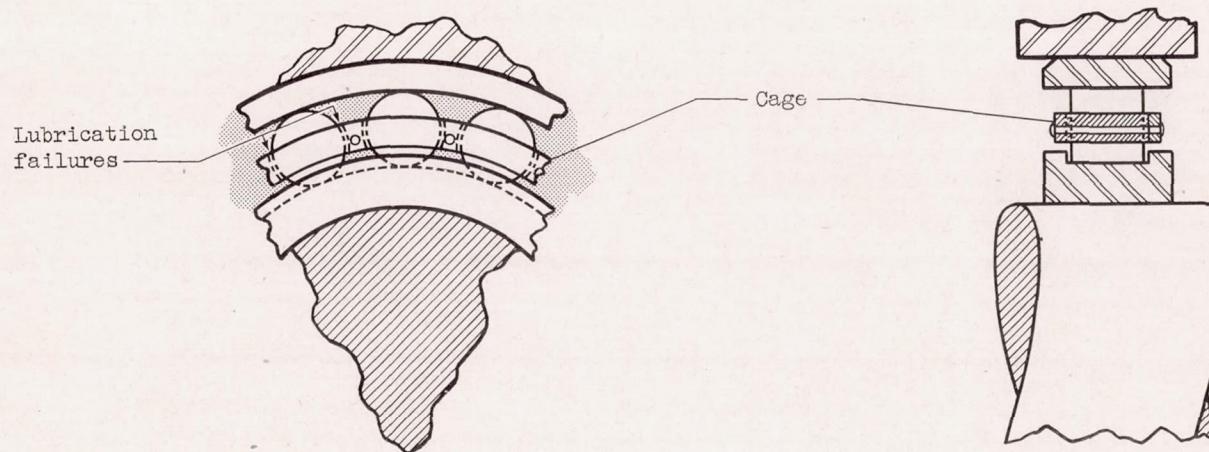
Cage

(b) Roller-riding cage.

Figure 1. - Location of lubrication failures at cage locating surfaces of rolling contact bearings.

(a) "L" nickel; etchant,
electrolytic oxalic.
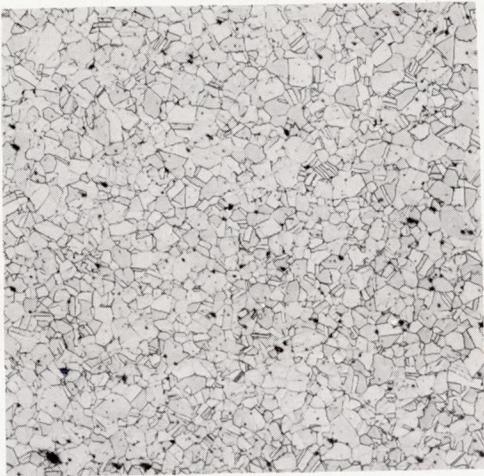
(b) Monel (wrought);
etchant, Carapella.

(c) Monel (cast);
etchant, Carapella.

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Figure 2. - Photomicrographs of metallographic specimens of nickel alloys used in wear and friction experiments. X100.
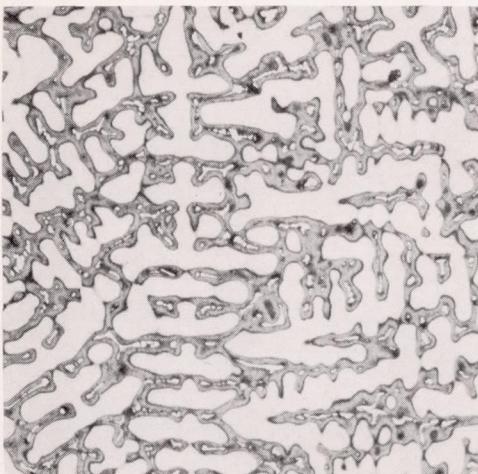
(d) "S" monel (cast);
etchant, Carapella.
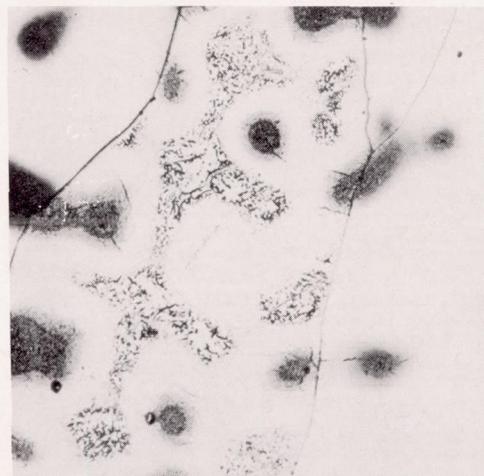
(e) Modified "H" monel
(cast); etchant, Carapella.

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(f) Invar (wrought);
etchant, Carapella.
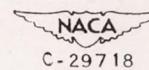
Figure 2. - Continued. Photomicrographs of metallographic specimens of nickel alloys used in wear and friction experiments. X100.

(g) Ni-Resist 3 (cast);
etchant, Carapella.

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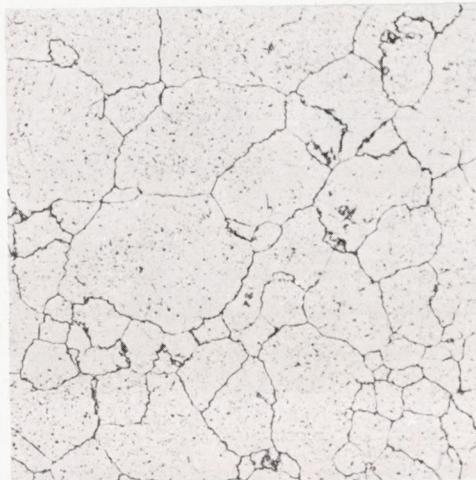
(h) Nichrome V (wrought);
etchant, electrolytic
oxalic.

Figure 2. - Concluded. Photomicrographs of metallographic specimens of nickel alloys used in wear and friction
experiments. X100.

Radial travel of rider
and restraining assembly

Radial-position scale

Friction-force
indicator

Rider-
assembly
motor

Pivot point

Load

Strain-gage
assembly

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CD-1720

Rider arm
Rider contact cam
Rider holder
Rider

Rotating disk
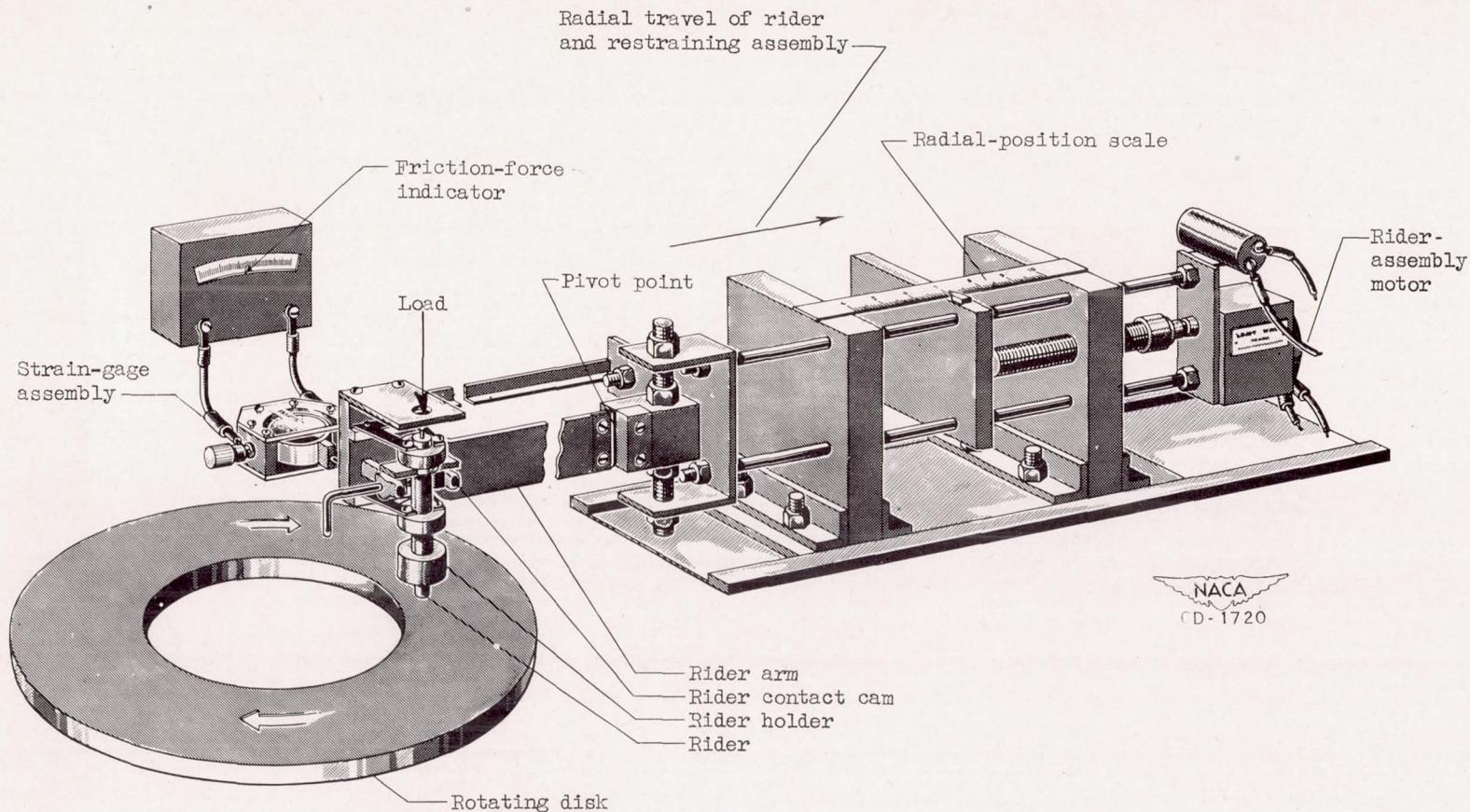
Figure 3. - Schematic diagram of sliding-friction apparatus.
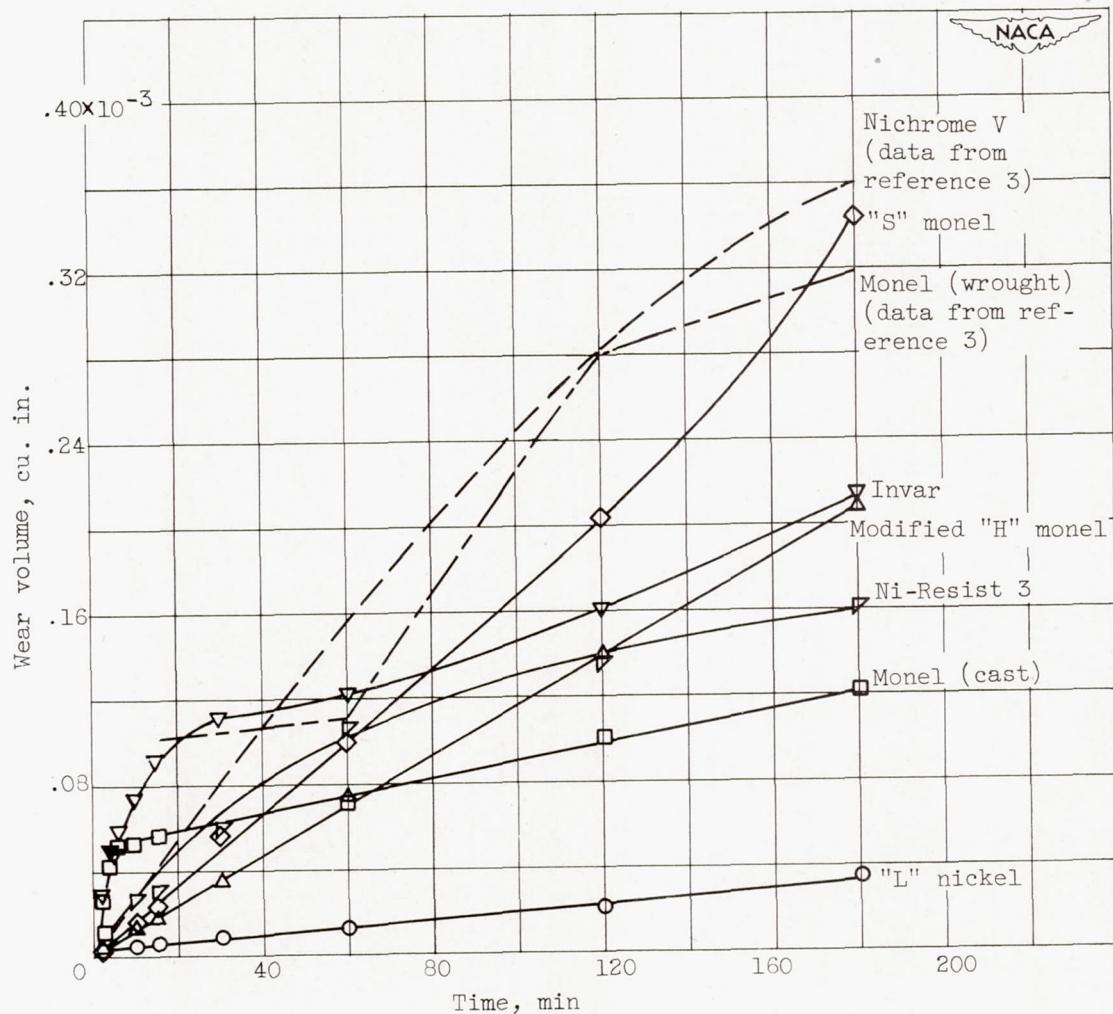
Figure 4. - Wear of several materials sliding against hardened SAE 52100 steel. Sliding velocity, 5000 feet per minute; load, 50 grams.
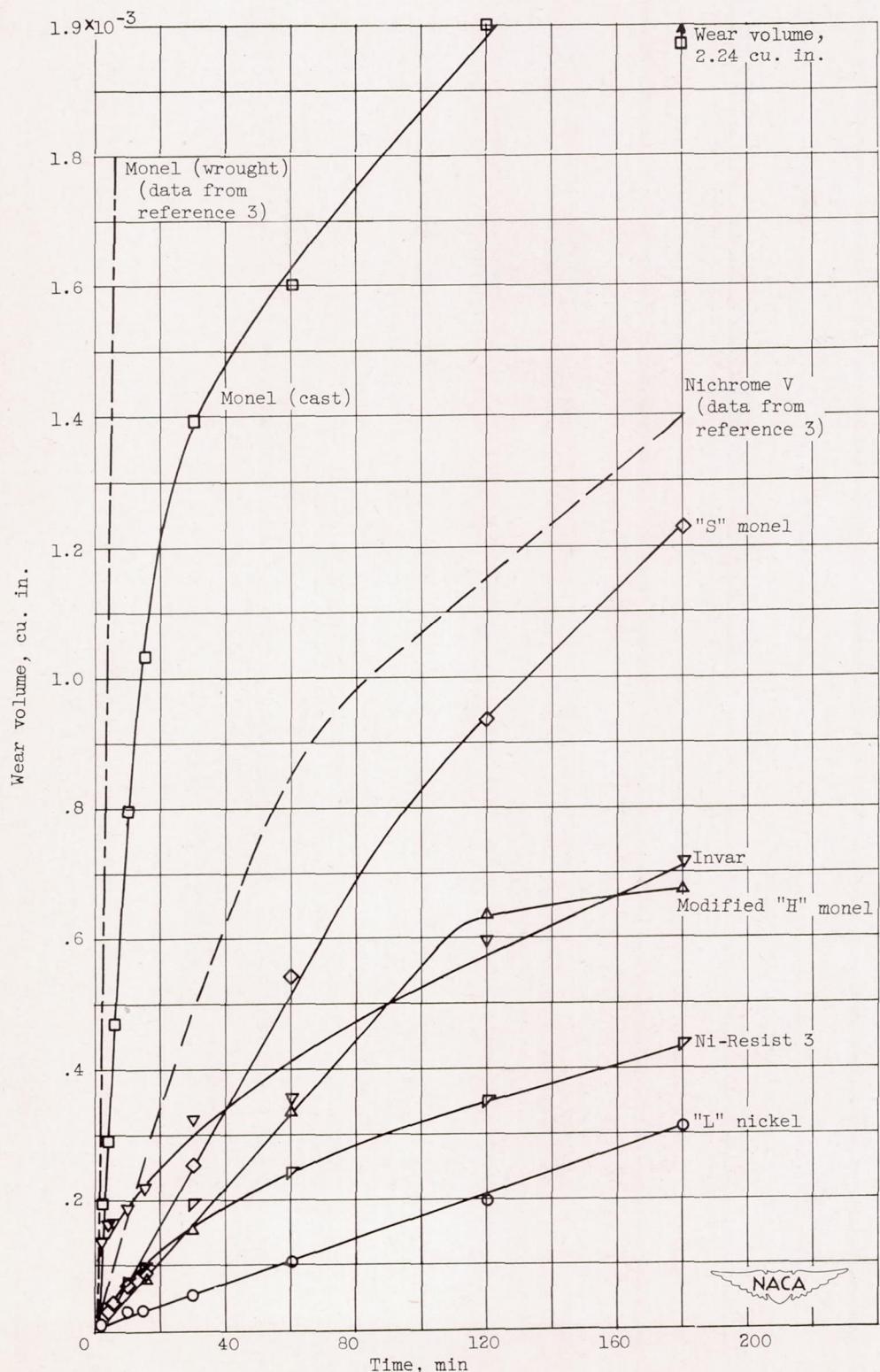
Figure 5. - Wear of several materials sliding against hardened SAE 52100 steel.
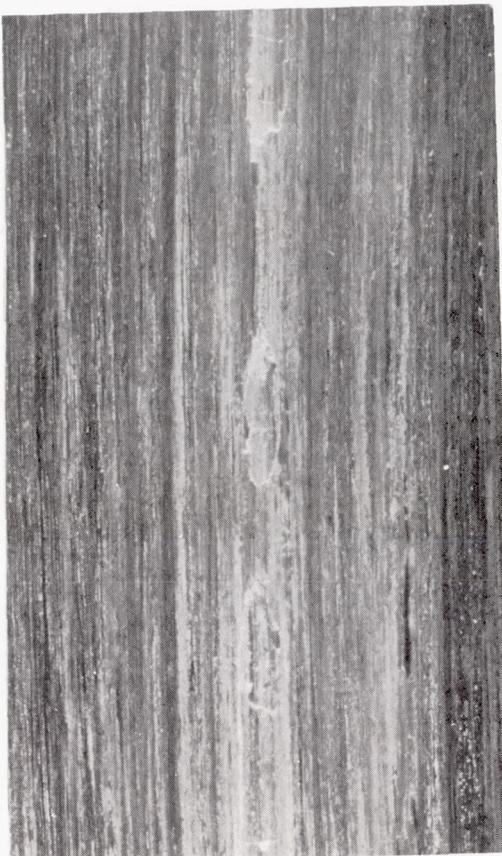Sliding velocity, 5000 feet per minute; load, 269 grams.
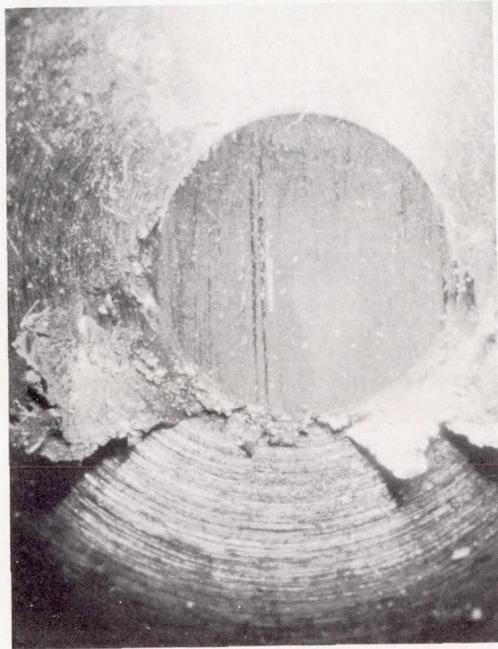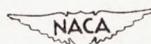
(a) "L" nickel.   C-29720   (b) Monel (cast).

Figure 6. - Wear areas of rider specimens of various materials after 3-hour operation against hardened SAE 52100 steel without lubrication. Sliding velocity, 5000 feet per minute; load, 50 grams; X15.
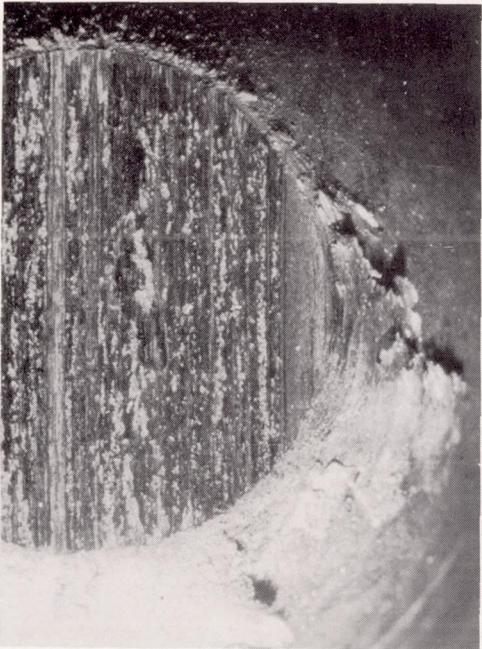
(a) "L" nickel.
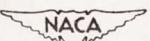
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(b) Modified "H" monel.

Figure 7. - Wear areas of rider specimens of various materials after 3-hour operation against hardened SAE 52100 steel without lubrication. Sliding velocity. 5000 feet per minute: load. 269 grams; X15.
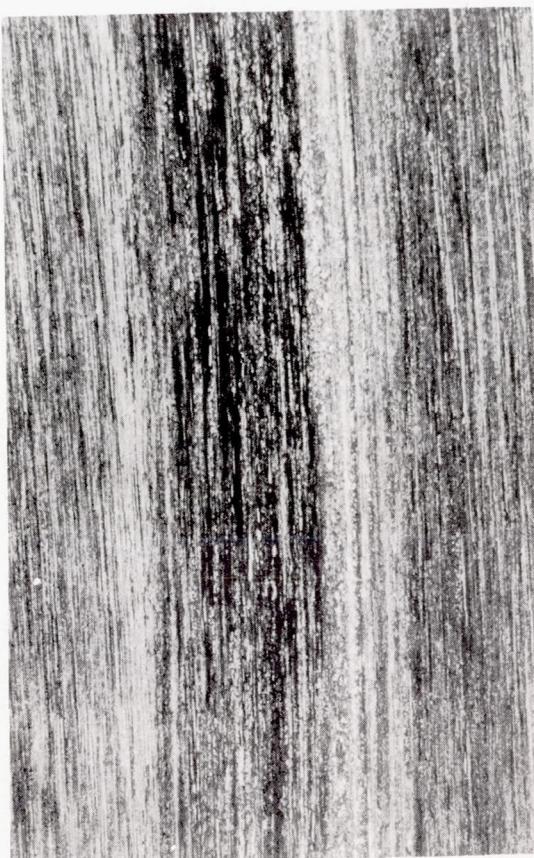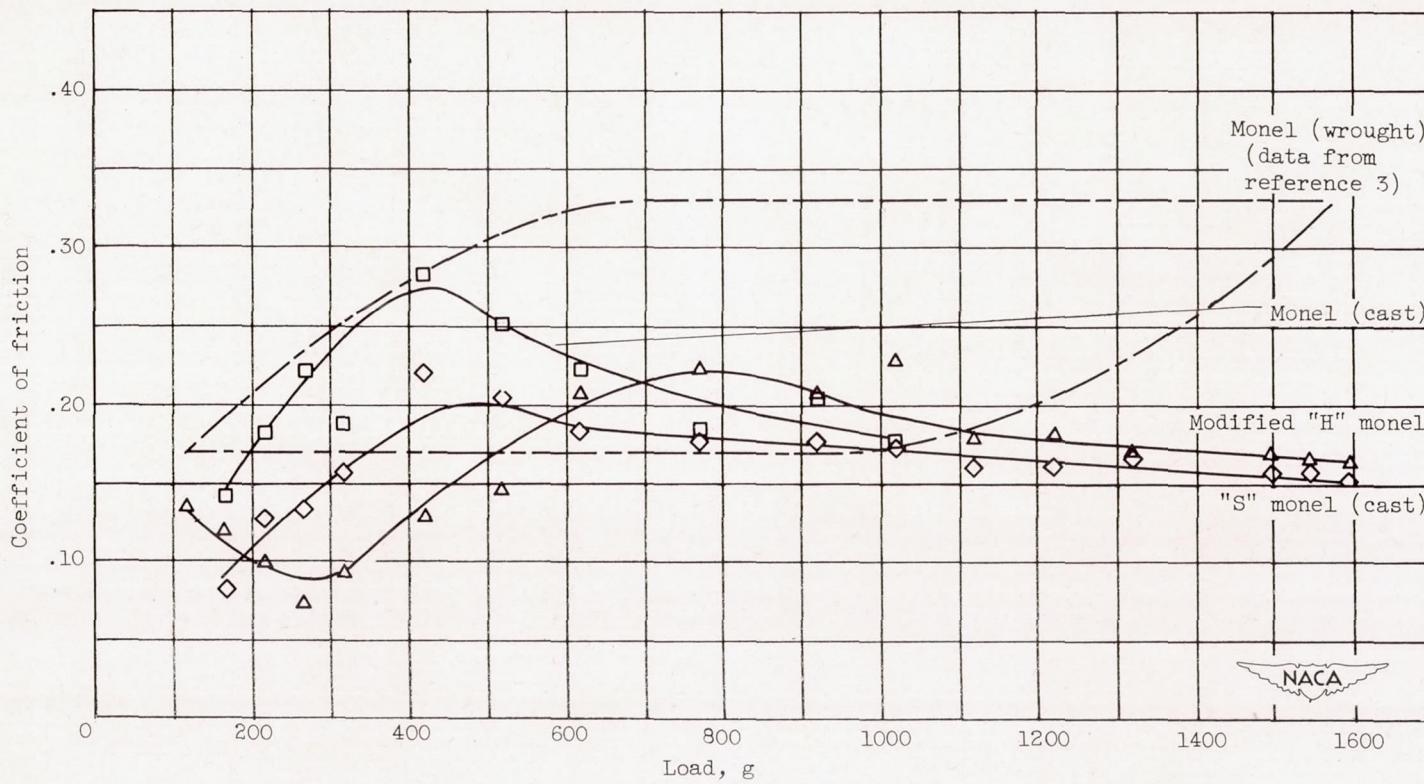
(a) "L" nickel. (Fig. 7(a)
shows mating surface.)

(b) Modified "H" monel.
(Fig. 7(b) shows mating surface.)

Figure 8. - Wear tracks on disk specimens of hardened SAE 52100 steel after 3-hour operation using sliders of various materials without lubrication. Sliding velocity, 5000 feet per minute; load, 269 grams; X15.

(a) Monel (cast), modified "H" monel, "S" monel, and Monel (wrought).

Figure 9. - Effect of load on friction of several materials sliding on hardened SAE 52100 steel boundary lubricated with grade 1005 turbine oil. Sliding velocity, 5000 feet per minute.
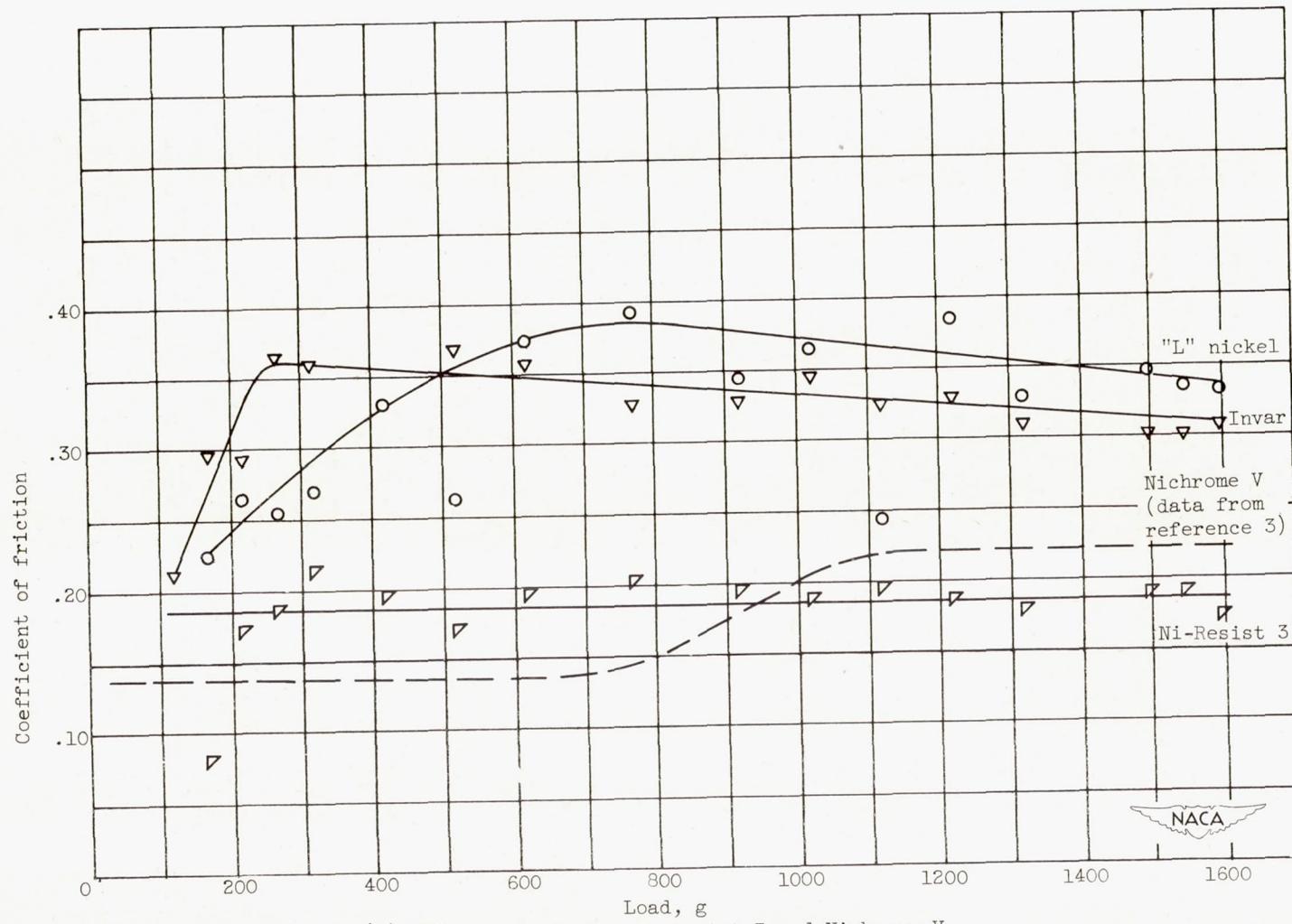
(b) "L" nickel, Invar, Ni-resist 3 and Nichrome V.

Figure 9. - Concluded. Effect of load on friction of several materials sliding on hardened SAE 52100 steel boundary lubricated with grade 1005 turbine oil. Sliding velocity, 5000 feet per minute.
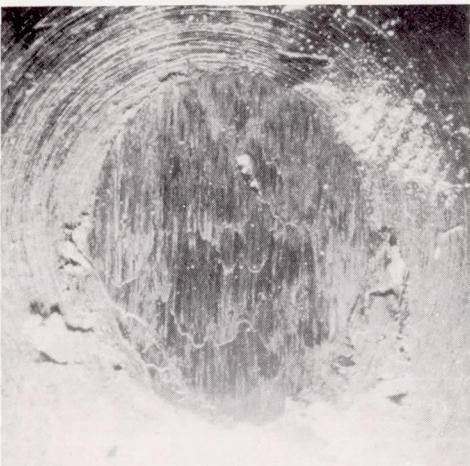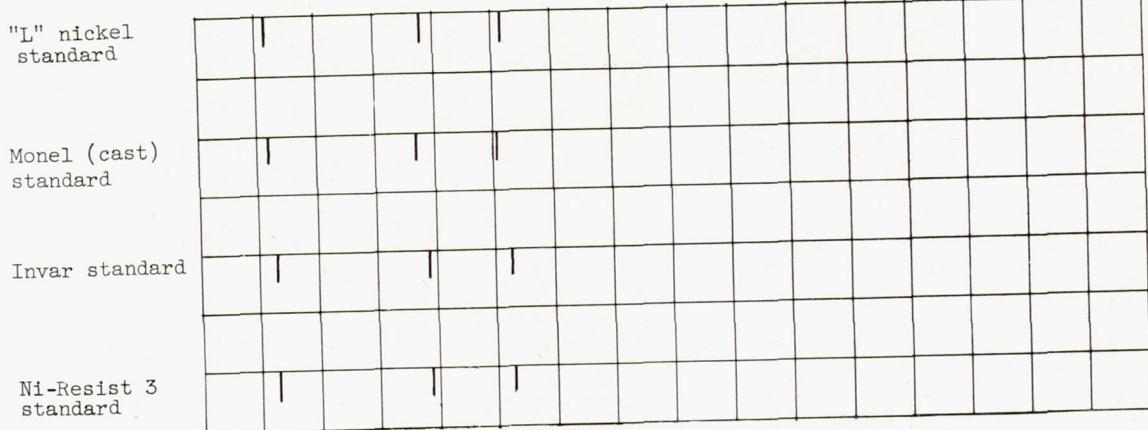
(a) "L" nickel.

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(b) Modified "H" monel.
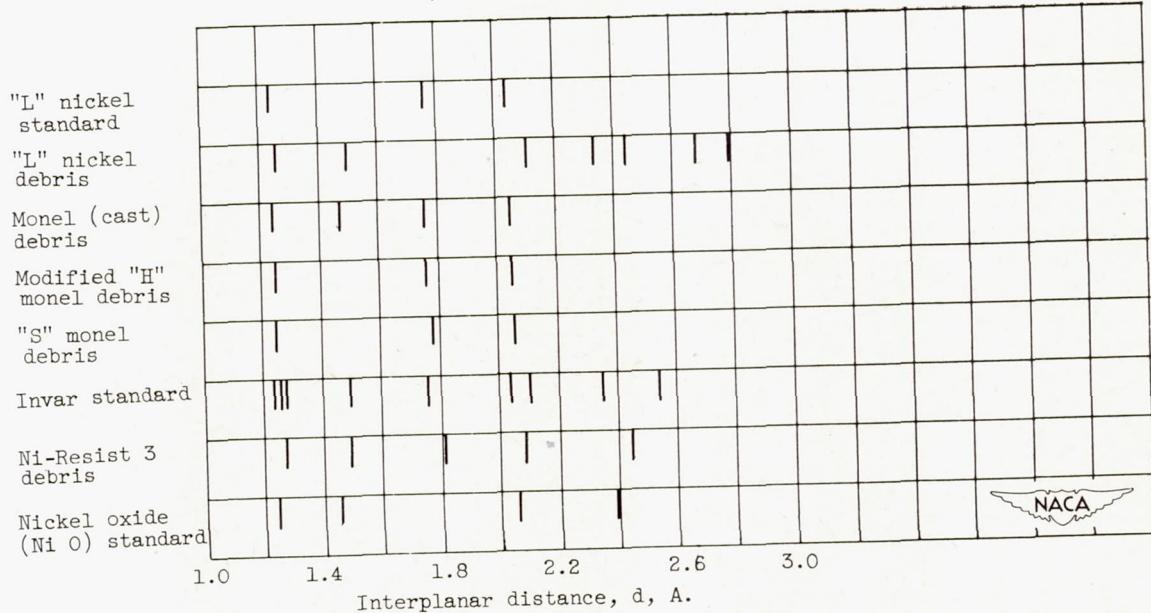
Figure 10. - Wear areas of rider specimens of various materials after sliding against hardened SAE 52100 steel boundary lubricated with grade 1005 turbine oil. Sliding velocity, 5000 feet per minute; load, 119 to 1593 grams; X15.

"L" nickel
standard

Monel (cast)
standard

Invar standard

Ni-Resist 3
standard

(a) Comparison of standard patterns.

"L" nickel
standard

"L" nickel
debris

Monel (cast)
debris

Modified "H"
monel debris

"S" monel
debris

Invar standard

Ni-Resist 3
debris

Nickel oxide
(Ni O) standard

1.0   1.4   1.8   2.2   2.6   3.0

Interplanar distance, d, A.

(b)   Comparison of patterns from debris with standard patterns from "L" nickel
and nickel oxide (Ni O).

Figure 11. - X-ray diffraction data for wear debris of nickel alloys run 3 hours in wear
experiments with 269-gram load at sliding velocity of 5000 feet per minntes.